Development of an Operational Multi-sensor and Multi-channel Aerosol Assimilation Package Using NAAPS and NAVDAS

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LONG-TERM GOALS

Accurate prediction of regional and global scale aerosol phenomena is crtical to military operations, especially over regions of interests such as Middle East.   For this reason, the US Navy developed the first operational global aerosol model in the world. Yet the forecast accuracy is limited by lack of observations over ocean and other data-poor areas. The long-term goal of this study is to improve the Navy's electro-optical propagation forecast capability through the use of multi-channel and multi-sensor aerosol data assimilation.

OBJECTIVES (abstract from proposal)

Due to the significance of aerosol particles in visibility forecasting, air pollution, and global climate change studies, the modeling and successful prediction of aerosol events is of great interest to both military and civilian users. Recognizing this interest, the Naval Research Laboratory Marine Meteorology Division developed the Navy Aerosol Analysis and Prediction System (NAAPS), the world's only truly operational aerosol prediction model. NAAPS provides both aerosol and visibility forecasts for fleet operation. A recent study showed that by ingesting over-ocean satellite observations into NAAPS through data assimilation, NAAPS forecasting capability could be improved by 20-40%. This research effort, however, also found that there are fundamental issues remaining that must be addressed before a global (i.e., over both ocean and land) aerosol data assimilation can realistically be ported to operational use. These include needs for:

(1)   Developing an over-land (with bright surface areas) aerosol data assimilation capability;

(2)   Improving observational data coverage through a multi-sensor data fusion/data assimilation technique;

(3)   Utilizing multi-channel information to improve the accuracy of NAAPS aerosol vertical profiles and speciation; and

(4)   Developing a better parameterization for characterizing model forecasting errors

We are investigating these issues and are developing a multi-sensor and multi-channel aerosol assimilation package using Level 2 aerosol products from the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 5, MODIS Deep Blue, Cloud-Aerosol Lidar and Infrared

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Pathfinder Satellite Observation (CALIPSO), and Advanced Along Track Scanning Radiometer (AATSR).   We will also integrate geostationary, polar orbiting, and even surface network data as they become available. This research will be transitioned for operational use at the Fleet Numerical Meteorological and Oceanographic Center (FNMOC), and will greatly advance air quality, visibility, and climate programs that, by necessity, are increasingly interested in applying aerosol data assimilation techniques.

APPROACH

The idea of assimilating satellite and ground-based observations is based in the more traditional means of assimilating state meteorological properties such as temperature and wind for the most basic of numerical weather prediction models. However, the assimilation of satellite observed aerosol signals for aerosol and visibility prediction is a new and challenging field. One reason why is because the advancement of operational aerosol and visibility forecasting models has only recently reached a point in recent years where it is possible to consider near real time data assimilation. Moreover, as demonstrated by recent studies, extensive bias and noise exist in even the most widely used satellite aerosol products, which further limits the use of such data for aerosol and visibility forecasts.

The goal of this study is to improve the Navy's electro-optical propagation forecast capability through the use of multi-channel and multi-sensor aerosol data assimilation. In the first part of this study, extensive effort was directed at characterizing the uncertainties of the satellite aerosol products including MODIS, MISR, and AVHRR. Each product was evaluated for its bias as a function of lower boundary conditions (e.g. surface albedo, and near surface wind), aerosol microphysics properties, and atmospheric conditions. Inter-product comparisons were also conducted to study cognitive and correlated biases. Bias removal procedures and noise suppression steps were developed for constructing data-assimilation-friendly products.

As a second goal, the newly developed data-assimilation-quality products were incorporated into the operational aerosol data assimilation using NAVDAS-AOD. The current version of NAVDAS-AOD was developed from the univariate two-dimensional capabilities of the NRL Atmospheric Variation Data Assimilation System (NAVDAS). Development of new and advanced capabilities within NAVDAS-AOD is in progress, such as the assimilation of 3-D space-borne lidar data and the assimilation of aerosol size parameters.

After extensive validation and testing, data-assimilation-quality satellite products and the new versions of NAVDAS-AOD, with advanced capabilities, will be delivered to NRL for further implementation in FNMOC for operational aerosol and visibility forecasts.

WORK COMPLETED

Two significant and exciting research efforts related to multi-sensor assimilation were conducted (collaborating with NRL scientists Dr. Jeff Reid, Dr. Edward Hyer, and Dr. James Campbell): (1) multi-sensor data assimilation over land and ocean using data-assimilation-quality over land and ocean MODIS and MISR aerosol products; and (2) coupling of 2-D aerosol assimilation (using MODIS and MISR products) with 3-D aerosol assimilation from CALIPSO data. Both exercises show very promising results as discussed in the next section. Manuscripts for the related studies are in preparation.

Other accomplishments include an evaluation of decadal regional and global aerosol trends using data-assimilation-quality MODIS, operational MODIS, and operational MISR over-ocean products. This study, following last year's research activities, is currently being published as an ACPD paper that is under review as a potential ACP publication.

We also finalized an analysis of the over-ocean MODIS aerosol product. This study is currently being published at the ACPD journal site and is under review for a ACP publication. We also participated in research efforts lead by Dr. Hyer and Dr. Reid from NRL on the development of a data-assimilation-friendly over-land MODIS aerosol product. This study is under review for an AMT publication.

The AVHRR aerosol product is considered to be a low scientific quality product due to limited spectral channels and relatively coarse spatial resolution. However, it has a long and inherited history, and most importantly, we are expecting AVHRR sensors to remain functioning even in the post-MODIS and MISR era. In collaboration with Dr. Hyer and Dr. Reid from NRL, we evaluated the NOAA Advanced Clear-Sky Processor for Ocean (ACSPO) product and studied the inclusion of the AVHRR aerosol product as a backup for the Navy's operational aerosol forecasts.

Finally, we evaluated the MODIS fine mode to total aerosol optical depth (η) product for multi-channel assimilation capability. The development of new versions of noise-reduced and bias-corrected MISR and MODIS Deep Blue aerosol products is currently being pursued.

RESULTS

Multi-sensor data assimilation using the data-assimilation grade over land and ocean MODIS and MISR aerosol products
Multi-sensor data assimilation and its impacts on both over ocean and over land aerosol forecasting capabilities were evaluated using the data assimilation quality MODIS over-ocean, the data assimilation quality MODIS over-land (collaborating with Dr. Hyer and Dr. Reid from NRL), and Version 1 of the quality-assured MISR aerosol products (a new version is under development). For one year of evaluation (2007) against AERONET ground-based data, our study suggested that NAVDAS-AOD could improve the accuracy of the analysis field over both land and ocean, with a 40% reduction in absolute error over ocean, and a 24% reduction in absolute error over land. Our study also suggested that over-ocean aerosol analyses benefited from the MODIS aerosol product, but adding more sensors only resulted in small improvements. However, multi-sensor assimilation is critical to the over-land aerosol assimilation method. Improvements are observable with each new sensor added [Zhang et al., BACIMO, 2010; Zhang et al., Aerosol Observability Workshop, 2010].

Coupled 2-d and 3-d aerosol assimilation using the CALIPSO, MISR, MODIS aerosol products
Following last year's 3-D CALIPSO data assimilation research efforts (in collaboration with Dr. James Campbell and Dr. Jeff Reid from NRL), we improved the representation of the observational and background error statistics of the 3-D version of NAVDAS-AOD. Extensive sensitivity studies were conducted for evaluating the performance of the system. Lastly, we examined the possibility of assimilating both 2-D satellite aerosol data (MODIS, MISR) with the 3-D aerosol data (CALIPSO), using a coupled 2-D and 3-Dvar aerosol assimilation package. Surprisingly, contrary to the common belief of the community, we found that including CALIPSO data would reduce the absolute error by more than 10% for the 48-h over land aerosol optical depth prediction (Figure 1). However, less improvement was found for the Root-Mean-Square-Error (RMSE) metric, indicating that the inclusion

of the 3-D CALIPSO data improves over land aerosol forecasts downwind, but not as much near source regions. Nevertheless, this exercise proves that CALIPSO data, although sparse in coverage, could still be used for improving aerosol and visibility forecasts. This encouraging result suggests that usage of near real time 3-D space-borne lidar products from future sensors may become important data sources for Navy needs. A manuscript is in preparation.

A decadal regional and global trend analysis of aerosol optical depth using data-assimilation grade over-water MODIS and Level 2 MISR aerosol products (abstract from the ACPD paper, Zhang and Reid, 2010)
Using ten years (2000-2009) of data-assimilation quality Terra MODIS and MISR aerosol products, as well as 7 years of Aqua MODIS data, we studied both regional and global aerosol trends over oceans. This included both natural and data assimilation grade versions of the products. Contrary to some previous studies that showed a decreasing trend in aerosol optical depth (AOD) over global oceans, after correcting for what appears to be aerosol signal drift from the radiometric calibration of both MODIS instruments, we found MODIS and MISR agreed on a statistically negligible global trend of 0.0003 / per year. Our study also suggests that AODs over the Indian Bay of Bengal, east coast of Asia, and Arabian Sea show statistically significant increasing trends of 0.07, 0.06, and 0.06 per ten years for MODIS, respectively. Similar increasing trends were found with MISR data, but with less relative magnitude. These trends reflect respective increases in the optical intensity of aerosol events in each region: anthropogenic aerosols over the east coast of China and Indian Bay of Bengal; and a stronger influence from dust events over the Arabian Sea. Negative AOD trends are found off the coasts of Central America, the east coast of North America, and the west coast of Africa. However, confidence levels are low in these regions, which indicate that longer periods of observation are necessary to be conclusive.

An analysis of the collection 5 MODIS over-ocean aerosol optical depth product for its implication in aerosol assimilation (abstract from the ACPD paper, Shi et al., 2010)
As an update to our previous use of the Collection 4 Moderate Resolution Imaging Spectroradiometer (MODIS) over-water AOD data, we examined ten years of Terra and eight years of Aqua Collection 5 data for their potential use in aerosol data assimilation. Uncertainties in the over-water MODIS AOD were studied as functions of observing conditions, such as surface characteristics, aerosol optical properties, and cloud artifacts. Empirical corrections and quality assurance procedures were developed and compared to collection 4 data. After applying quality assurance and empirical correction procedures, the Root-Mean-Square-Error (RMSE) in the MODIS Terra and Aqua AOD are reduced by 30% and 10–20%, respectively. Ten years of Terra and eight years of Aqua quality-assured level 3 MODIS over-water aerosol products were produced. The newly developed MODIS over-water aerosol products will be used in operational aerosol data assimilation and aerosol climatology studies, and will also be useful to other researchers who are using MODIS satellite products in their projects.

Evaluation of the potential of using the AVHRR ACSPO product as a backup satellite product
AVHRR sensors have been providing continuous observations of the Earth and atmospheric system for decades, and will continue providing weather and environmental monitoring for the foreseeable future. As a backup to current and future satellite aerosol sensors (in collaboration with Dr. Hyer and Dr. Reid from NRL), we evaluated aerosol retrievals from the NOAA Advanced Clear-Sky Processor for Ocean (ACSPO) products, including their potential as a backup for the NRL aerosol forecasting and assimilation system. Although this is still an ongoing research effort, our preliminary results show that with the use of the noise-reduced and bias-removed AVHRR aerosol retrievals, the accuracy of the

NAAPS AOD analysis field indeed improved. This result supports possible future implementation of AVHRR into Navy visibility forecasts.

Analysis of the MODIS over ocean fine mode to total aerosol optical depth ratio for multi-channel aerosol assimilation
We studied MODIS-derived over-ocean fine mode to total aerosol optical depth (η) values for multi-channel aerosol assimilation. η is often used as a surrogate for aerosol type, as large η values are generally related to fine mode aerosols, such as sulfate and smoke aerosols, and small η values typically indicate sea salt and dust aerosols. A data-assimilation-quality η product is developed by applying bias corrections and noise removal procedures to data from the seven MODIS channels that report aerosol property values along with a spectral convolution method from O'Neil et al. (2003) that is used to estimate modified/corrected η values. Also, a software update to NAVDAS-AOD that assimilates MODIS η is currently under development.

Further development of the data-assimilation-quality MODIS Deep Blue and MISR aerosol products
Continuing from last year's effort, we are in the process of evaluating MODIS Deep Blue and MISR aerosol products. In particular, inter-satellite product comparisons are being conducted for indentifying problematic regions where point validations from AERONET data are not available. A manuscript describing this work is in preparation.

IMPACT/APPLICATIONS

The Observing System Simulation Experiments (OSSEs) suggests that multi-sensor data assimilation is necessary for improving NAAPS over-land aerosol and visibility forecasting capabilities. Also, inclusion of 3-D CALIPSO data can improve aerosol forecasts, especially over downwind regions, despite the sparse spatial coverage of this dataset.

TRANSITIONS

New patches for the NAVDAS-AOD have been transitioned to NRL.

The first version of the data-assimilation-quality AVHRR *ACSPO* product has been delivered to NRL Monterey for evaluating its potential use in operational forecasts.

RELATED PROJECTS

This project is tightly coupled to a number of ONR 32 programs at the Marine Meteorology Division Aerosol and Radiation Section associated with further development of the Navy's aerosol forecasting capabilities.   This includes an integrated effort with the Earth Sciences Applications project of J.S. Reid for developing NAVDAS-AOD, model integration with the Large Scale Aerosol Modeling Development project of D. L. Westphal, and a new start project (N00014-10-0816) of Dr. Jianglong Zhang. Lastly, we are beginning enhancements to 3-D and 4-D variational analysis in cooperation with the NRL data assimilation section (Bill Campbell and Nancy Baker).

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HONORS/AWARDS/PRIZES

Graduate student Yingxi Shi has been selected as one of the recipients of the NASA Earth and Space Science Fellowship.
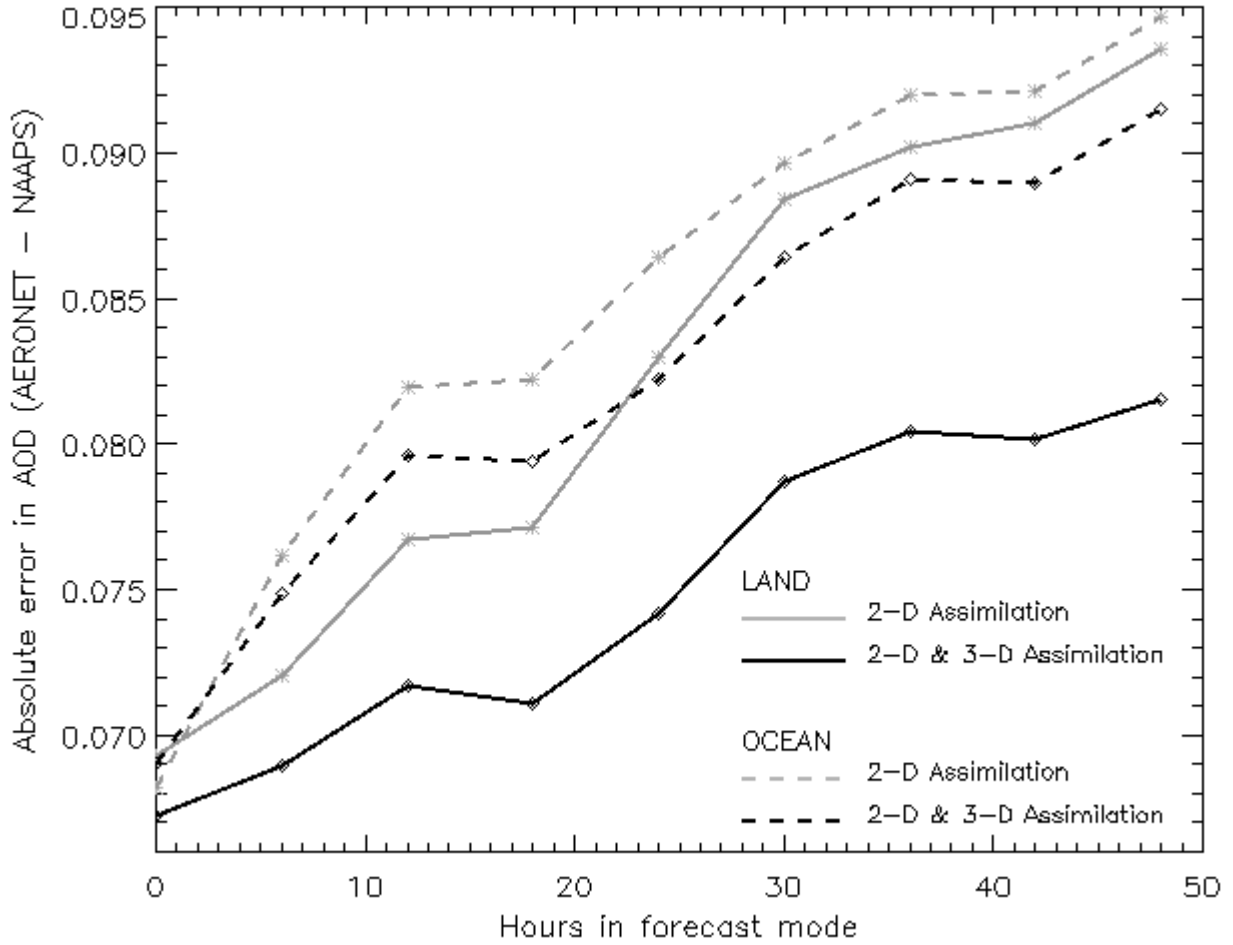
Figure 1. Two month (June–July 2007) averaged differences between AERONET and NAAPS as a function of number of hours in forecast mode for both over ocean (coastal and island AERONET sites, dashed lines) and over land (solid lines) cases. The 2-D and/or 3-D NAVDAS-AOD runs were only applied at the forecasting time 0 h. The data-assimilation-quality over land and ocean MODIS aerosol products and version 1 of the data-assimilation-friendly MISR aerosol product were used in the 2-D aerosol assimilation steps. The quality assured CALIPSO data were used in the 3-D aerosol assimilation. The light grey lines show the scenario when only 2-D assimilation was applied at the forecasting time 0 h, and the black lines show the scenario when the coupled 2-D and 3-D assimilation was applied at the forecasting time 0 h.